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From Nature-Based to Ecologically Enhanced Beach Protection Strategies: an Experimental Comparison

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Abstract: Low crested structures (LCS) are increasingly used around the world to protect coastlines imitating the protection service provided by natural reefs and helping to enhance or recover other ecosystem services. The importance of these environmentally friendly coastal structures has led to the developments of new types of LCS and armor blocks, which encourage the settlement and colonization of marine species on the structure. This study describes two-dimensional physical tests carried out to investigate the behavior of three types of LCS (two of them using innovative armor elements), designed to protect a stretch of sand dune-beach system under different wave conditions. The comparison of the hydrodynamic, morphological and biological performance of these novel protection strategies and traditional concrete cubes shows they are an eco-friendly feasible alternative for the protection of coastal zones.

Keywords: Low-crested structures; Armor units; Beach-dune evolution; Concrete modular blocks; Coral shaped reef.

1 Introduction

In recent years, low-crested structures (LCS) have been used more often as protection strategies in coastal zones; their design reduces the economic, aesthetic and environmental costs and impacts of an emerged breakwater. Placed in relatively shallow depths, LCS can be made of a wide variety of prefabricated concrete units. The main criteria in the design and selection of these units are: hydraulic and structural stability, manufacturing, storage, handling, placement, maintenance and repair (Burcharth et al. 2015). However, in the worldwide scenario of future ecosystem service loss, due to the degradation of coral reefs, new shapes of prefabricated units are being developed, which focus on letting LCS better reproduce the performance of natural reefs in terms of their ecological functions. These artificial solutions go some way to eluding the difficulties, uncertainties about long-term success and cost issues still prevailing in ecological restoration projects.

Coastal interventions, which are environmentally friendly can be grouped into 5 classifications: (a) nature-based, (b) engineered ecosystems, (c) soft engineering, (d) ecologically enhanced hard infrastructure and (e) de-engineering, after Silva et al. 2017. Natured-based infrastructure can be used where habitat conservation and restoration are still viable; measures may be adopted to increase the ecological resilience of the ecosystems providing the services of interest. On the other hand, ecologically enhanced beach protection strategies refer to those adaptations of traditional civil infrastructure design, in order to imitate natural ecosystem functioning. The new types of armor units designed to enhance ecosystem service provision can be considered such an intervention. Examples of these are: the ECOPODE^{TM}, which has a similar shape to the ACCROPODE^{TM} and is enhanced by adding roughness to its surface (Calabrese et al. 2011); the Eco Xbloc, whose rough surface, random structure and high porosity provides an attractive habitat (Bettington et al. 2011); and the perforated and non-perforated trapezoidal units analyzed by Sannasiraj and Sundar (2019).

In this study, experiments were carried out to analyze the hydrodynamic performance (transmitted and dissipated energy) of two novel LCS units and the morphological response of a stretch of sand dune-beach system protected by the structures. These results are contrasted with the performance of a LCS made of concrete cubes. The comparisons include the biological performance of the different structures tested, as well as their classification in terms of naturalness and the shore protection provided by them.

2 Experimental work

The laboratory tests were performed in the wave flume at UNAM (37.0 x 0.80 x 1.20 m). The prefabricated elements used to build the structures in the experiments were: 1) trapezoidal concrete modular blocks, 2) coral shaped elements and 3) the traditional concrete cubes (see Fig. 1). The artificial coral reef elements were placed onto the concrete modular units, as shown in Fig. 2b, in order to imitate the natural coral reef structure and geometry. For full details on this unit, see Mendoza et al. 2019.

Three different geometries and locations of the LCS along the beach profile were tested for each prefabricated element. These are called Submerged, Detached 15 and Detached 30 tests, according to their height and submergence (see Tab. 1, Fig. 2 and Fig. 3).

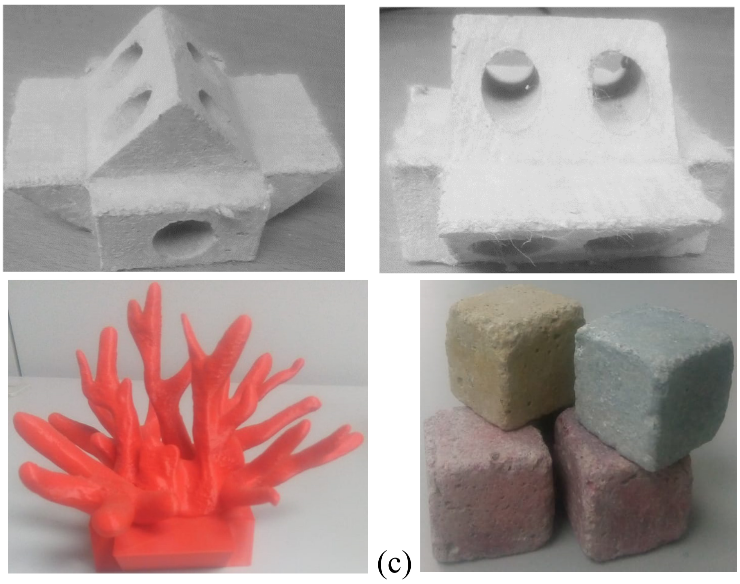

Fig. 1. Breakwater armor units: (a) Trapezoidal modular block; (b) coral shaped reef; (c) concrete cube unit.

Tab. 1. Definition of LCS.

LCS typology	Height (m)	Distance from the coastline (m)	Freeboard (m)
Submerged	0.15	3	0.20
Detached 15	0.15	2	0
Detached 30	0.30	3	0

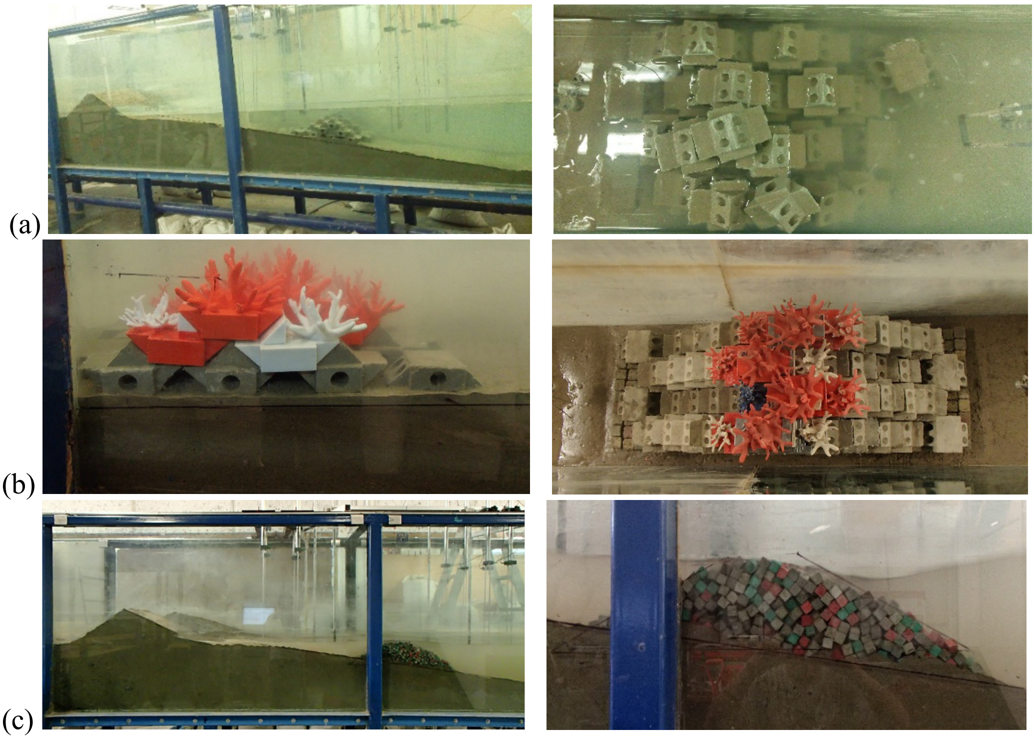

Fig. 2. Images of some of the tests in the wave flume: (a) trapezoidal modular block; (b) coral shaped reef; (c) concrete cubes.

The wave flume was divided into two for the last 8.0 m of its length, in order to incorporate two beach-dune profiles; with or without a berm on the beach, and two slight variations of beach slope and dune dimensions, Profile A and Profile B in Fig. 3. The evolution of the two beach profiles and the hydrodynamic behavior of the three LCS were tested for five selected irregular wave conditions (JOWSWAP spectrum) over a time of 45 minutes. Calm and storm scenarios were defined by the combination of two significant wave heights, two wave peak periods and two different water depths in the wave tank (Tab. 2). Measurements were taken by three wave gauges installed at the toe of the front face of the breakwaters and by two other wave gauges located shoreward, in order to analyze the wave transmission and energy dissipation by the structures.

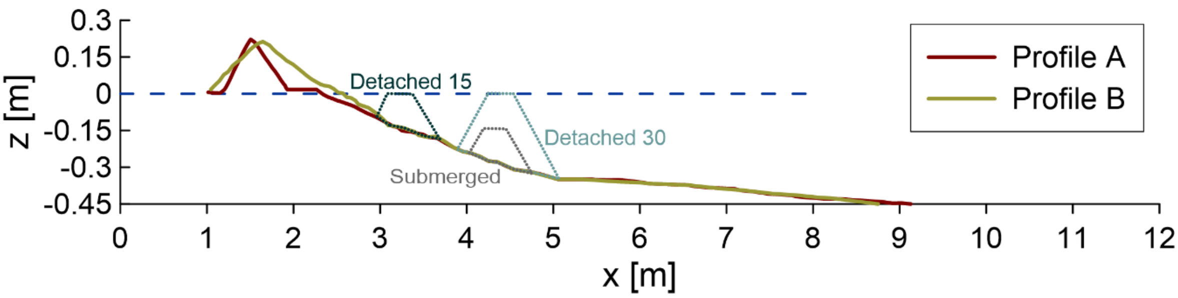

Fig. 3. Beach profiles: longitudinal-section views.

Tab. 2. Wave conditions in the experiments.

Test No.	Hs (m)	Tp (s)	Water depth in the tank (m)
1	0.05	0.894	0.45
2		1.118	
3	0.1	0.894	
4		1.118	
5	0.1	1.118	0.48

2.1 *Wave transmission*

Wave transmission coefficients were calculated as the ratio of the transmitted and incident root mean square wave heights (H_{rms}), as given by Eq. (1).

$$K_T = \frac{\mathrm{Hrms\_t}}{\mathrm{Hrms\_i}} \tag{1}$$

where K_T = transmission coefficient, H_{rms_t} = transmitted $H_{rms,}$ H_{rms_i} = incident H_{rms}

2.2 *Wave energy dissipation*

The wave energy dissipation due to the presence of the structures was estimated as the normalized energy flux damping defined by Eq. (2) and Eq. (3) (Lowe et al. 2007 and Rogers et al. 2016).

$$F_d = \frac{F_i - F_t}{F_i} \tag{2}$$

where F_d = ratio of dissipated wave energy flux, F_t = transmitted wave energy flux, F_i = incident wave energy flux

$$F = EC_g = \rho g \int S_p \left[\frac{\cosh(kh)}{\rho g \cosh(kh_i)}\right]^2 C_g(f)df \tag{3}$$

where F = wave energy flux, E = wave energy, C_g = wave group celerity, ρ = fluid density, g = gravity acceleration, S_p = wave spectrum

3 Results and discussion

3.1 *Wave transmission and energy dissipation*

For the Submerged, Detached 15 and Detached 30 scenarios, the wave transmission shows a generally decreasing trend for the whole set of wave conditions and profiles analyzed, (in blue, green and red, respectively, in Fig. 4). The change in the transmission coefficient is similar for the three types of armor units: higher than 0.7 for Submerged scenarios, 0.4-0.8 for Detached 15 scenarios and 0.2-0.6 for Detached 30 scenarios. In a few tests, the transmission coefficients were greater than 1, associated with steep but non-breaking waves over the structures. It is important to highlight the good results obtained from the coral and modular breakwaters, in particular for the Detached 30 arrangement, which are even better than those of the LCS made of concrete cubes.

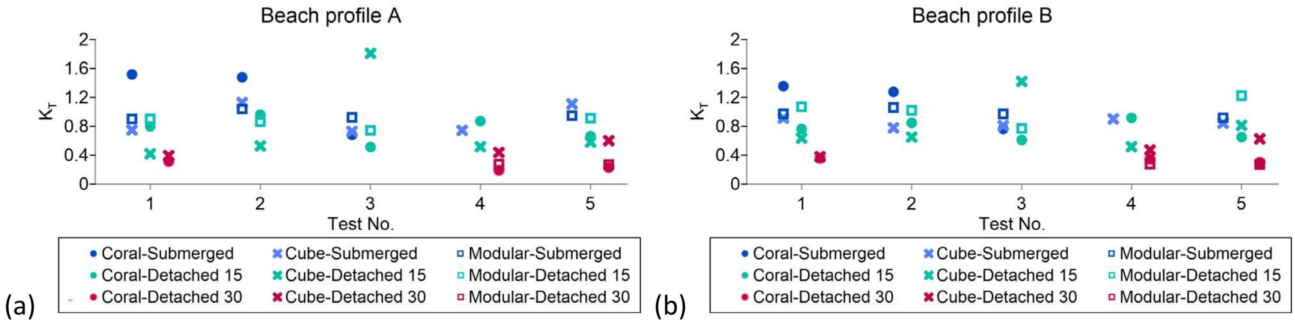

Fig. 4. Wave transmission coefficients in the laboratory tests: (a) Profile A; (b) Profile B.

As expected, lower effectiveness in energy dissipation was seen in the Submerged scenarios, compared to Detached 15 and Detached 30 (see Fig. 5, data in orange vs. data in blue and pink). The high energy dissipation found for all the units in the Detached 30 scenarios is surprising (ratio greater than 0.8). This performance is even better for the coral shaped units and modular blocks than for the

LCS made of cubes (see tests 4 and 5, for example). The differences between the results from profiles A and B were only noticeable in the tests of submerged structures (Fig. 5).

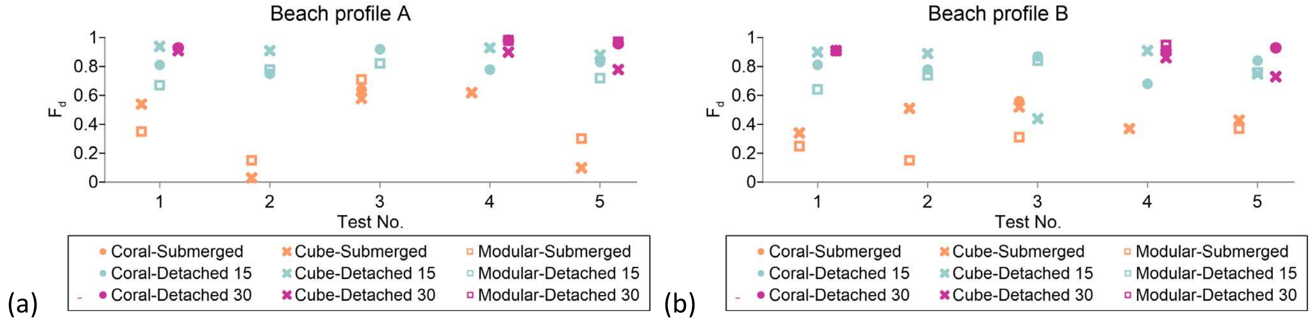

Fig. 5. Ratio of energy dissipation of laboratory tests: (a) Profile A; (b) Profile B.

3.2 *Beach profile evolution*

Four parameters were selected to compare the morphological changes in the beach-dune system behind the structures: the horizontal and vertical coastline displacements and the dry and submerged normalized sand volumes. The latter represent the change in sand volume for each test, related to the total sediment volume of the beach profile, as given by Eq. (4) and Eq. (5) for the variation of the emerged and submerged beach, respectively.

$$V_d = \frac{V_{fd} - V_{id}}{V_t} \tag{4}$$

$$V_s = \frac{V_{fs} - V_{is}}{V_t} \tag{5}$$

where V_d = dry normalized volume, V_s = submerged normalized volume, V_{fd} = final volume of dry beach, V_{id} = initial volume of dry beach, V_{fs} = final volume of submerged beach, V_{is} = initial volume of submerged beach. The four parameters were plotted in Fig. 6, 7 and 8 together with the transmitted wave height.

The transmitted wave height seems not to be dependent on the type of armor unit, nor the wave condition and nor the initial shape of the beach profile (see Fig. 6 to 8), with a higher value for Submerged scenarios and lower for Detached 15 and Detached 30. It is important to note that while only the potential energy was included in the calculation of transmission coefficients, the combined effects of potential and kinetic wave energy are reflected in the beach response.

Similarly, the sediment movement trends also were greater for the Submerged scenarios and less for the Detached 15 and Detached 30 scenarios. In general, for the submerged structures, an increase in wave height (from test 3) produced dune erosion and sand movement from the dry to the submerged part of the beach profiles, with the formation of a sand bar at the toe of the structures in their leeward side. The response in test 5 (increased water level) was the creation of a sand bar very close to the coastline and a loss of dune sand volume. In the Detached 15 scenarios, the sand also tends to accumulate at the toe of the breakwater, although some of it is transported further seaward. The Detached 30 configuration seems to be that which most favors beach stability, given that the loss of dry volume is least. When the sand moves from the emerged to the submerged part of the beach profile it accumulates at the toe of breakwaters. In this scenario a sand bar is also formed next to the breakwaters.

The comparison in the response of profiles A and B shows more sand moving from the emerged to the submerged beach in profile B, and a higher volume lost from the submerged beach for profile A, especially in Submerged and Detached 15 scenarios (Fig. 6 to 8). For all armor types, less coastline retreat was seen in profile B compared to that in profile A. The results for the coral and cube units are similar. The vertical coastline displacement was also lower in profile B than profile A, but with more difference seen between the types of armor elements.

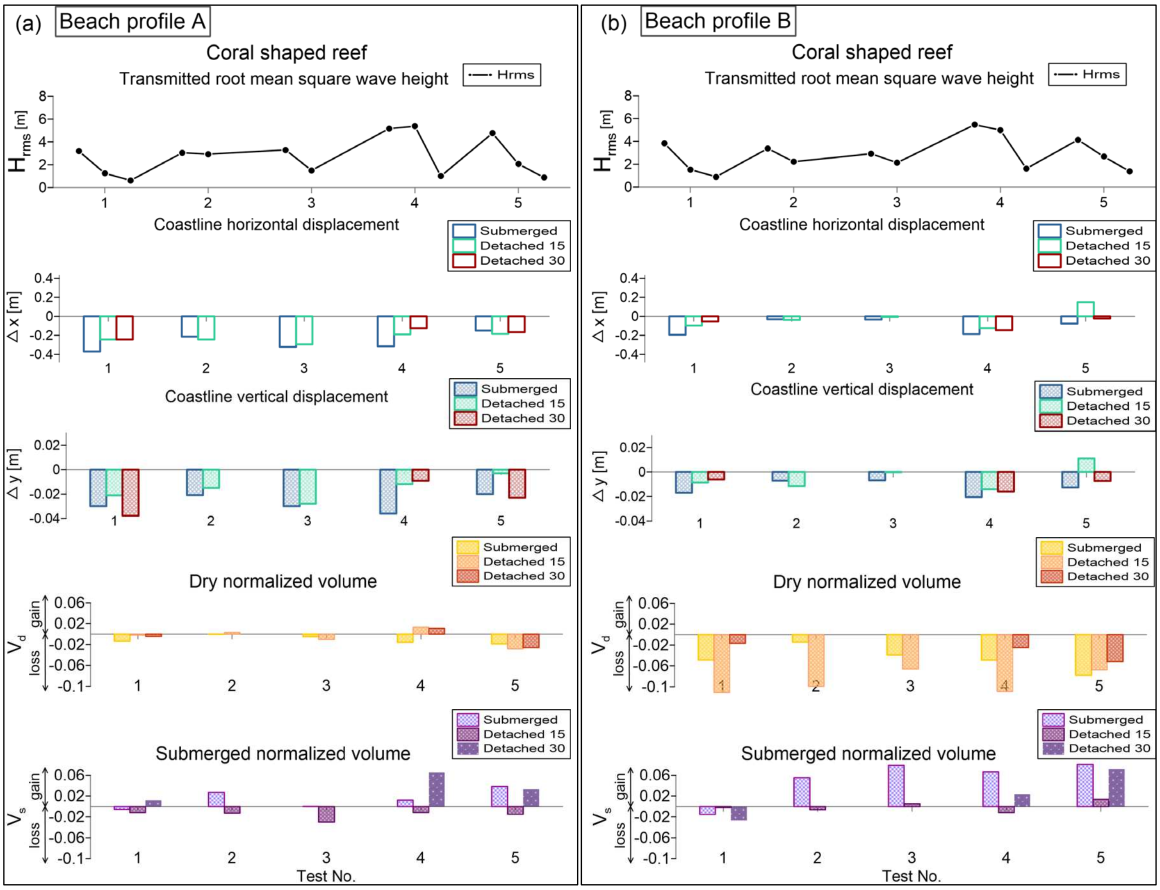

Fig. 6. Morphological response of beach profiles- Coral shaped reef units: (a) Profile A; (b) Profile B.

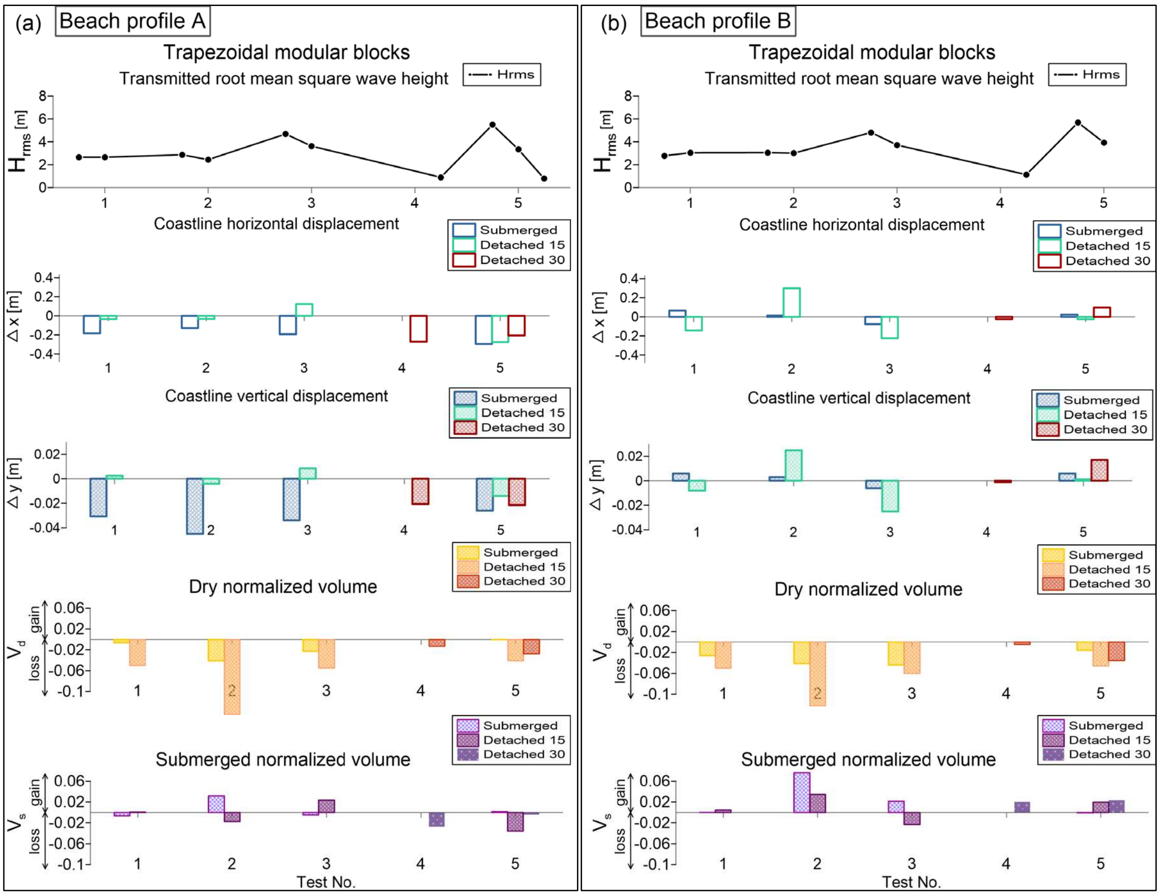

Fig. 7. Morphological response of beach profiles- Concrete modular blocks: (a) Profile A; (b) Profile B.

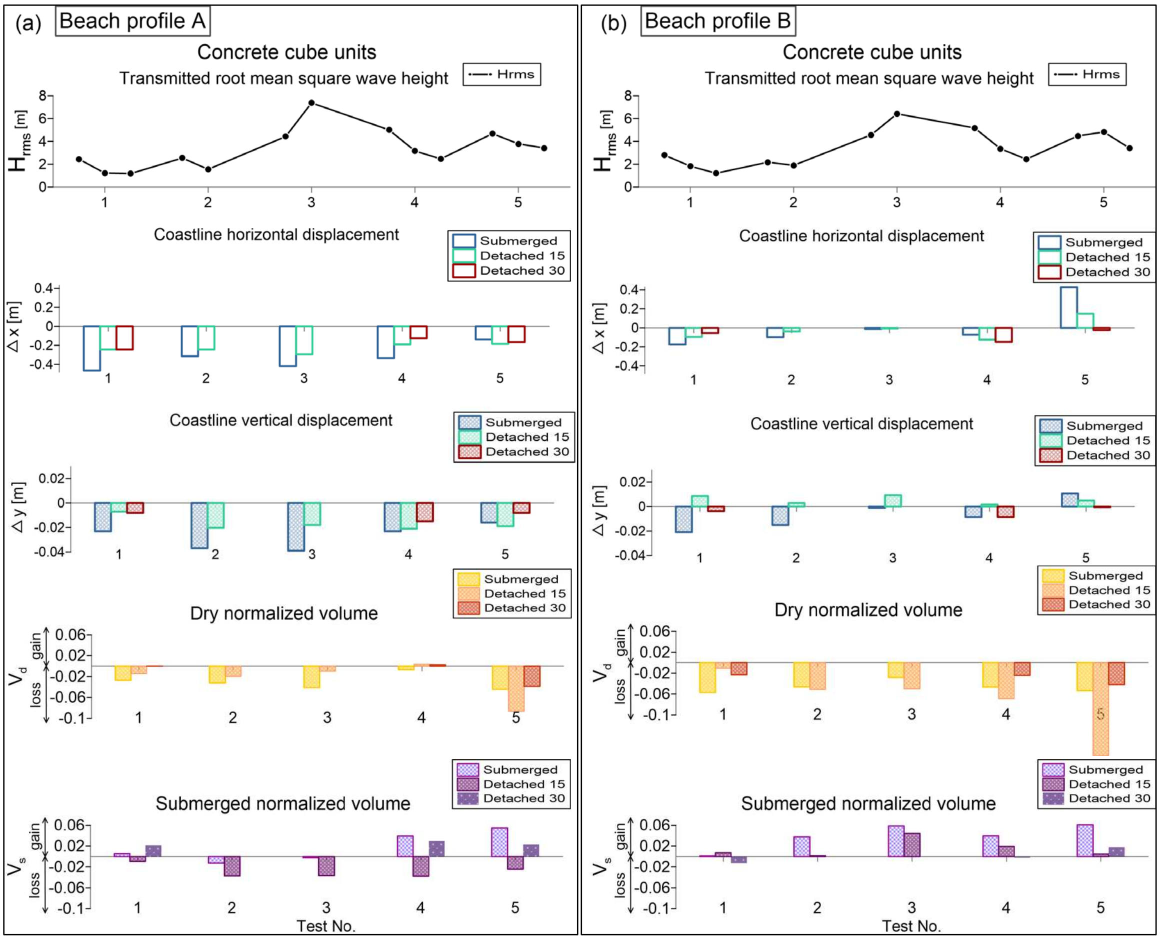

Fig. 8. Morphological response of beach profiles- Concrete cubes units: (a) Profile A; (b) Profile B.

3.3 Biological performance

Although this function of the armor units cannot be actually tested in the laboratory; from an environmental perspective, if the natural substratum is to be mimicked, the topographic complexity (roughness) and the stability of the coastal protection structures are the main features favoring colonization by benthonic organisms (Hawkins et al. 2010). Once the bottom is colonized, the food chain is likely to be developed. Water circulation and oxygenation are also fundamental for the survival of marine species; this means that some level of turbulence is also desirable for the habitat service to be provided. It is thus expected that, due to their greater complexity in shape and encouraged flow movement through their irregular structure, the coral shaped and the trapezoidal modular units used in this study will produce better ecological conditions than concrete cubes.

4 Conclusions

This paper presents a set of laboratory tests focused on evaluating the performance of LCS made of different armor units. These tests allowed comparisons of wave-structure interaction and the beach profile response in the presence of two novel structures with those derived from a structure made of concrete cubes. In general, the LCS made of the new units showed similar performances to the cube structure. Furthermore, for the most energetic waves, the novel units showed better wave energy control. The morphological response was also noticeably better for the coral shaped units (less sediment movement and more stable profiles). From the ecological point of view, the coral shaped reefs also seem to be the ones most easily colonized, while the modular elements may be the best for letting a food chain development.

The analysis presented here shows the importance of limiting the freeboard, as large waves may not break eliminating any beach protection. In turn, the location of the structure also impacts the efficiency of the hydrodynamic and morphologic performance characteristics that is, if the structure is placed farther from the coast a dissipative dynamic profile with a submerged bar may be formed. In contrast, LCS located near the coast tend to produce reflective profiles, which may not be desirable for future storm occurrence. In this way, the artificial coral reef crowned at mean sea level farthest from the coast gave the best hydraulic and morphologic functionalities.

While many challenges remain, the analysis presented in this paper aims to encourage coastal engineers to continue developing eco-friendly solutions for coastal protection.

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